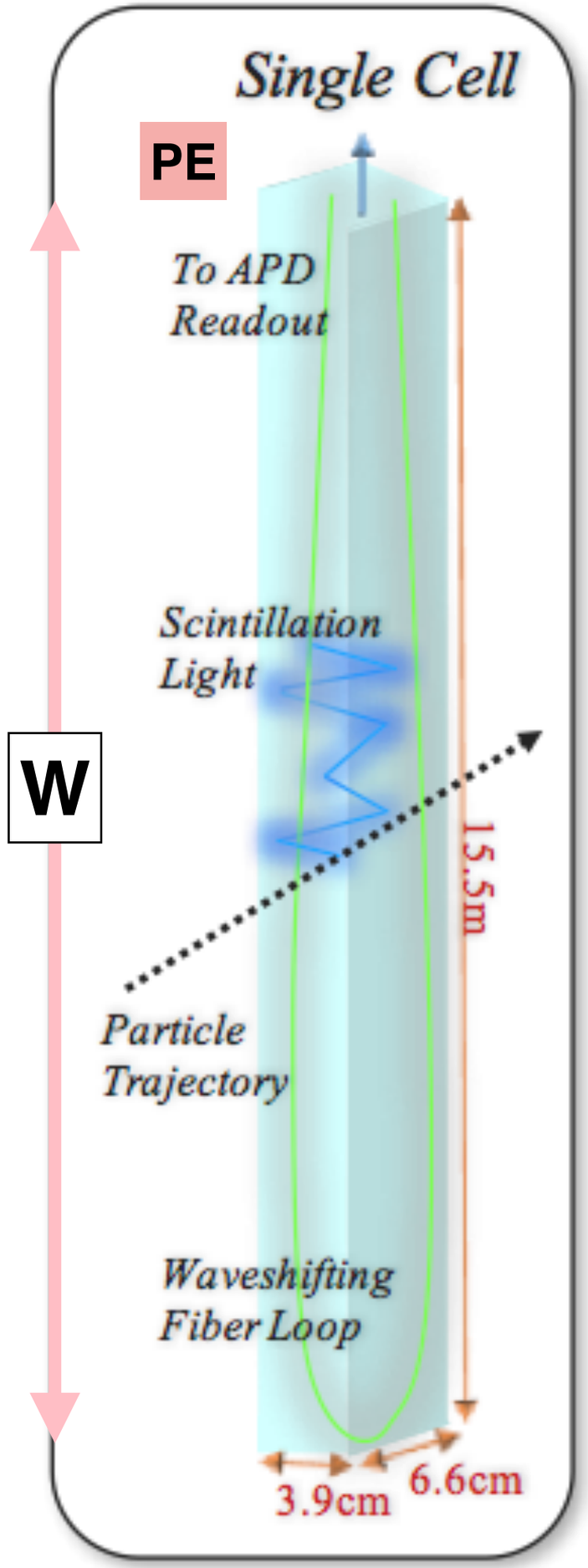
NOvA Calibration

Calorimetric Energy Scale in the NOvA Detectors



Tyler Alion

New Perspectives

6 June 2017

Outline: # Energy Calibration

Cosmic Muon Data and MC

PE
Photoelectrons

Rescaling of ADC to approximate photoelectrons

PECorr
Corrected

Effective PE with all relative effects calibrated out

GeV
Energy Deposited

Energy deposited by each hit

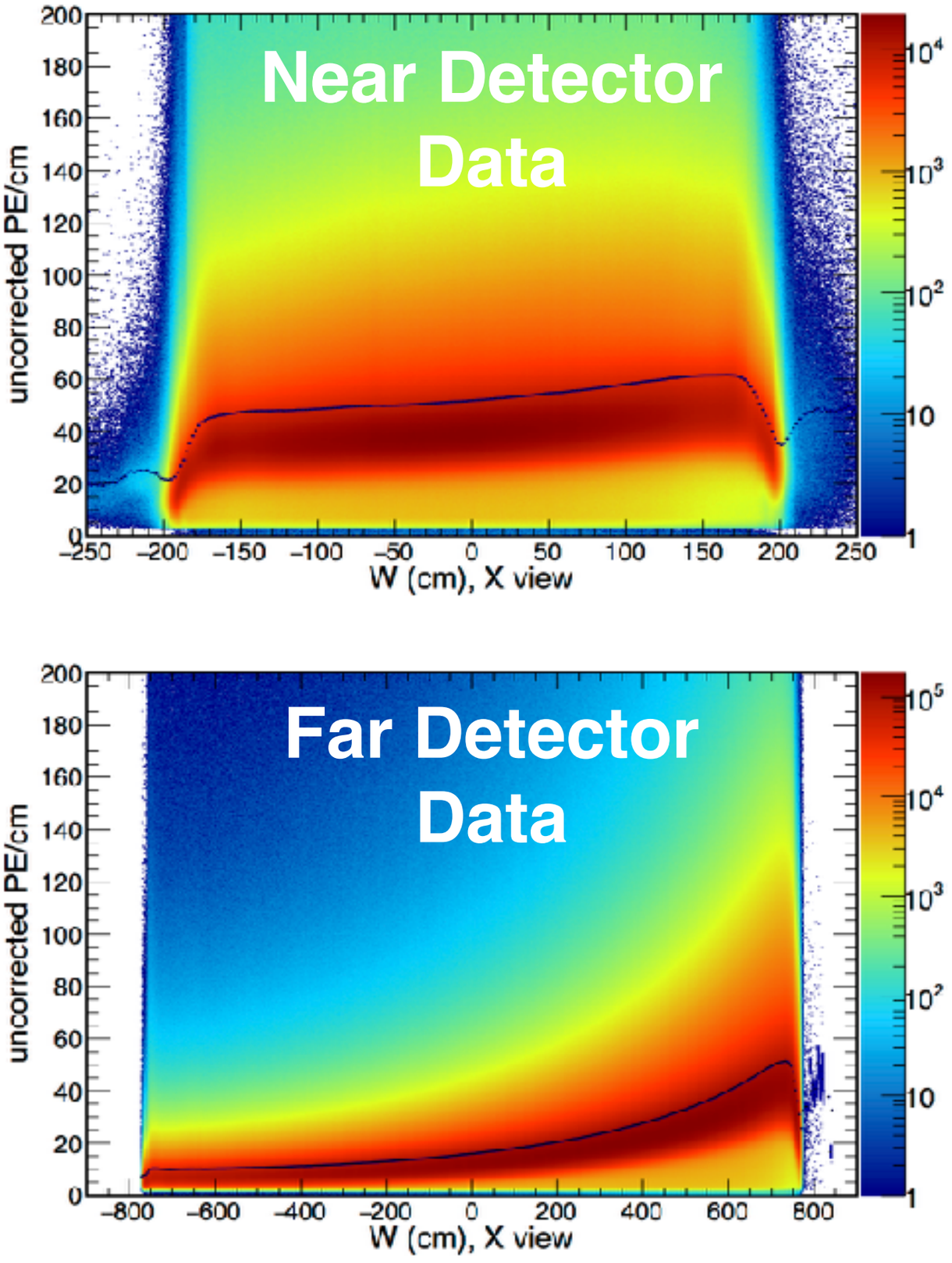
Relative Calibration

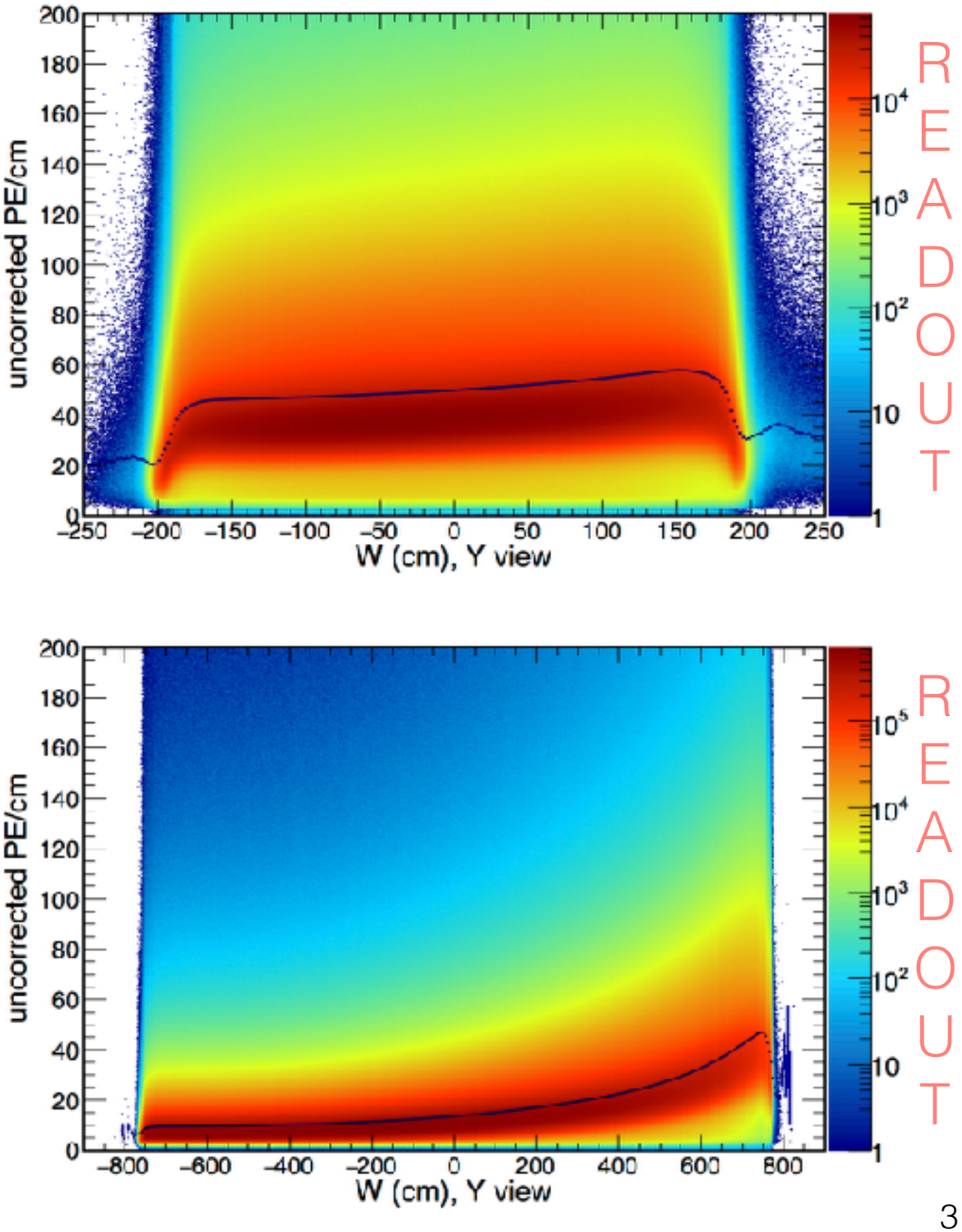
- **Attenuation** along length of a given **cell**
- Cosmic Muon Sample

Absolute Calibration

- Energy Scale Factor **(GeV/PECorr)**
- Stopping Cosmic Muon Sample

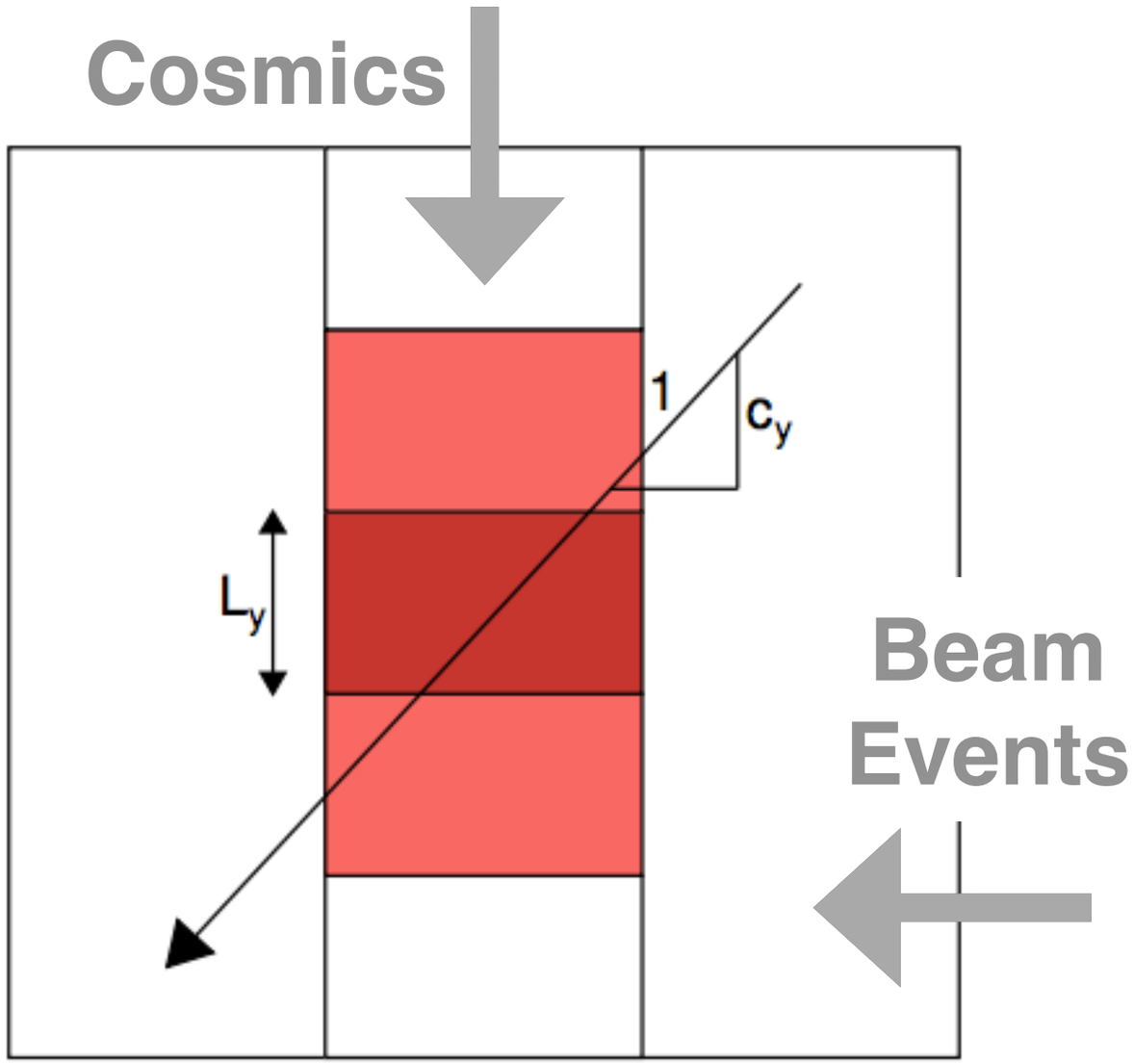
Attenuation of Scintillation Light





Cosmic Caveats

"Tricell" Hit Selection



path length = L_y / c_y

- **Tricell Criteria: Well known hit length**
  - require tricell hits to be between 2 other hits in the same plane of cells
- **Vertical Cell (X) View Hits**
  - Cosmics: longer, higher-PE, fewer
- **Horizontal Cell (Y) View Hits**
  - Cosmics: shorter, lower-PE, more
- **Threshold**
  - hits < ~25 PE not seen by readout.
- **Shielding**
  - Average true energy changes with vertical position
- Path length scales Energy deposition, so the **basic unit of calibration is Uncalibrated Response: PE/cm**

Relative Calibration

Correct hits to a unit which is
uniformly comparable throughout the detector,
and proportional to energy deposition

- Depends on: **Cell** and longitudinal position in cell, **W**
  - ✳ *Fit PE/cm attenuation profiles for each cell*

- Bias in cosmic muon sample must be corrected before attenuation fit — threshold, shielding

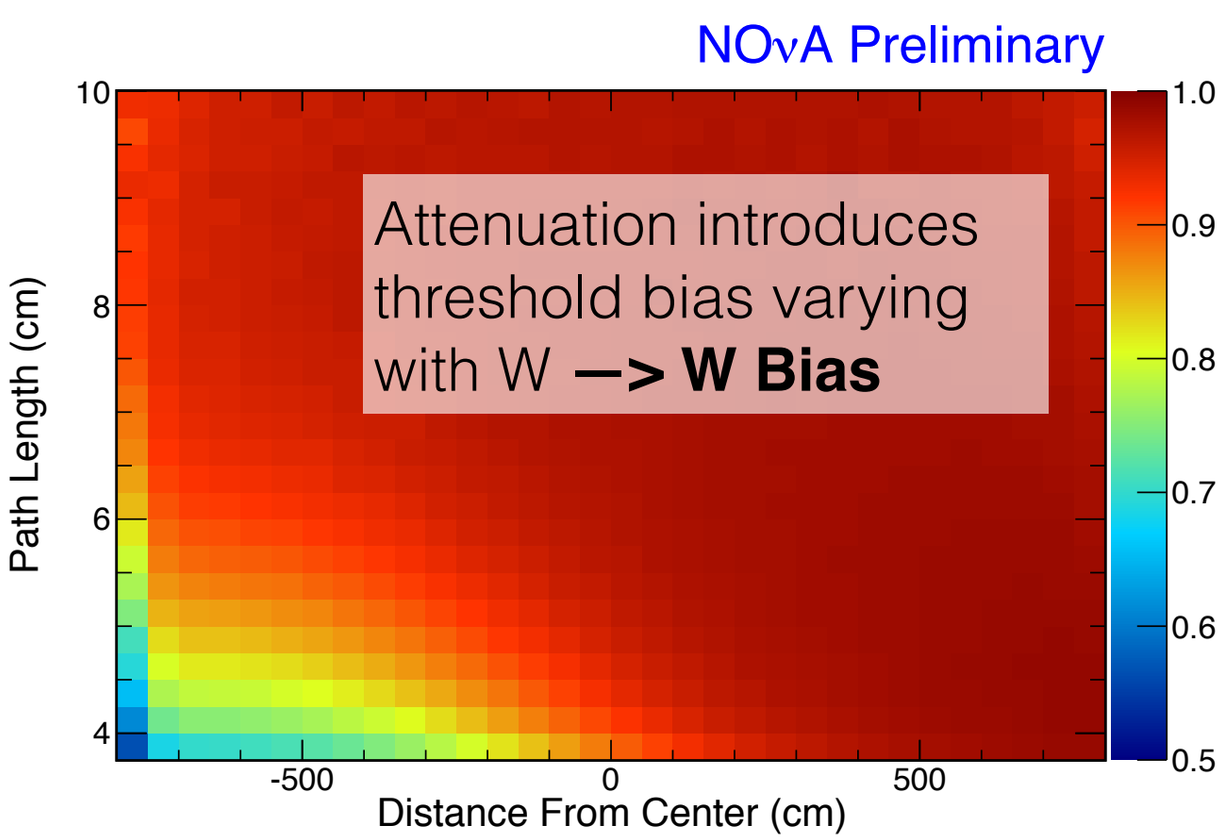
- **Threshold/Shielding Correction** depends on Cell, W (MC)
  - PE is poisson distributed
  - PE/cm vs W for each cell, look at E_{true}/E_{MIP}

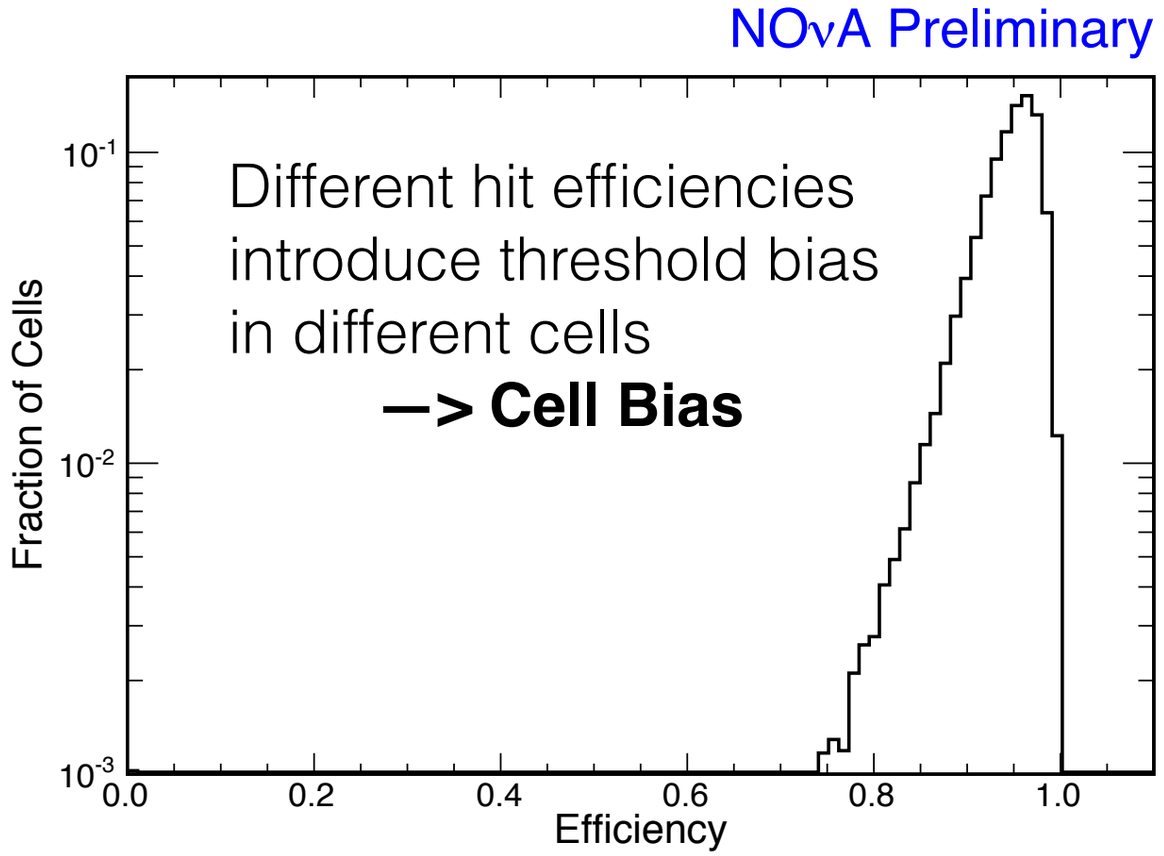
$$T = \frac{PE}{\lambda} * \frac{E_{\text{true}}}{E_{\text{MIP}}}$$

- **Attenuation Correction:** perform fit on threshold-and-shielding corrected PE/cm vs W plots
  - ✳ Fit for every cell in every plane

Hit Threshold

For a hit to be seen above threshold, the energy deposited may need to be an upwards fluctuation within the underlying Landau distribution

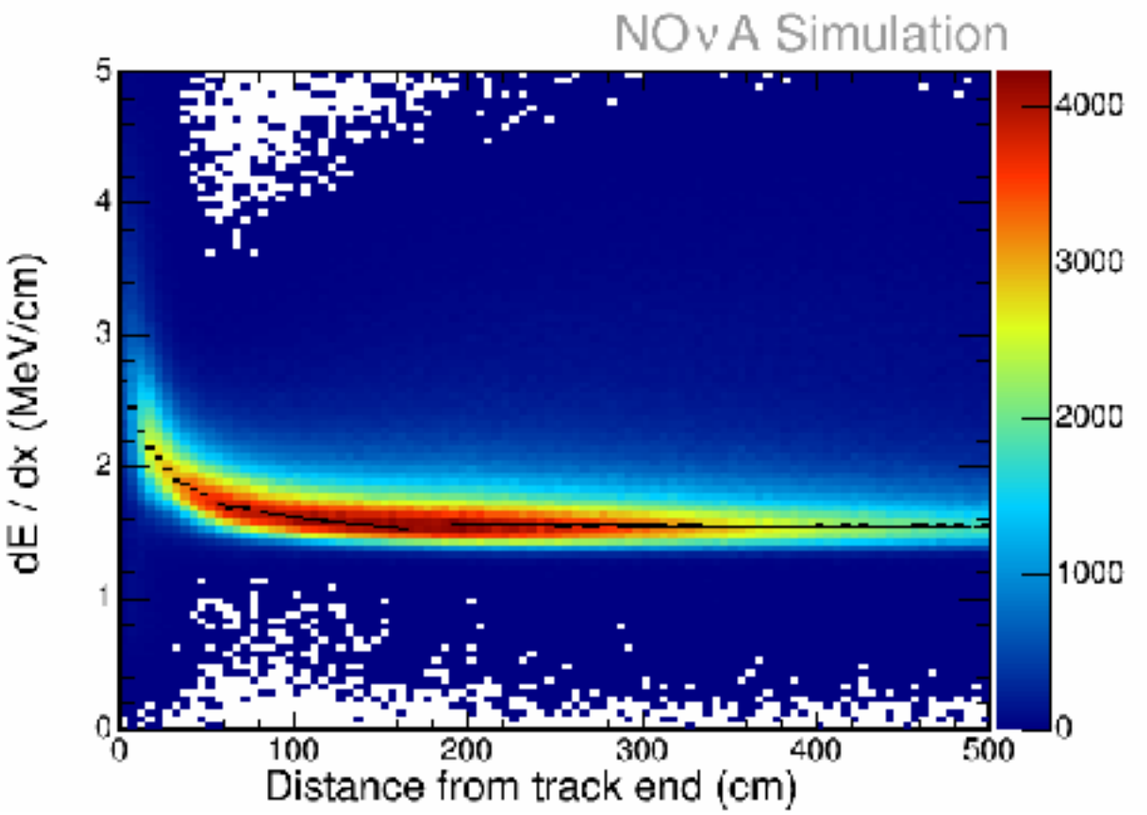


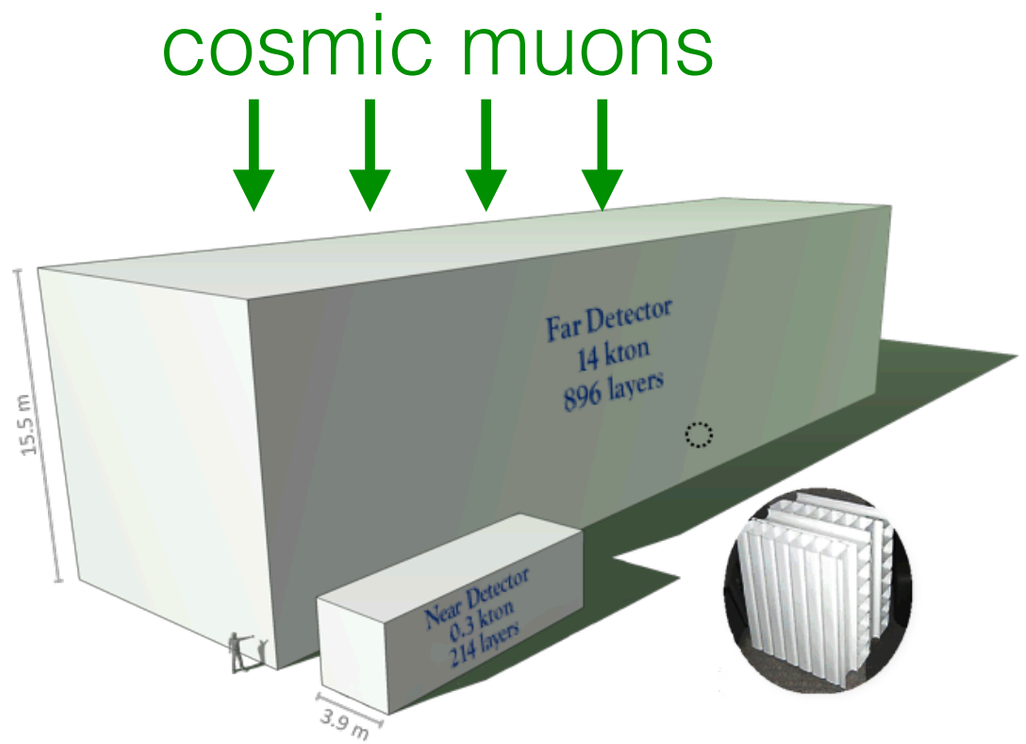


- Short MIP hits are impacted the most — Horizontal Y View
  - ✳ Especially hits which have attenuated
- Different cells throughout the detector affected to a different degree

Detector Shielding

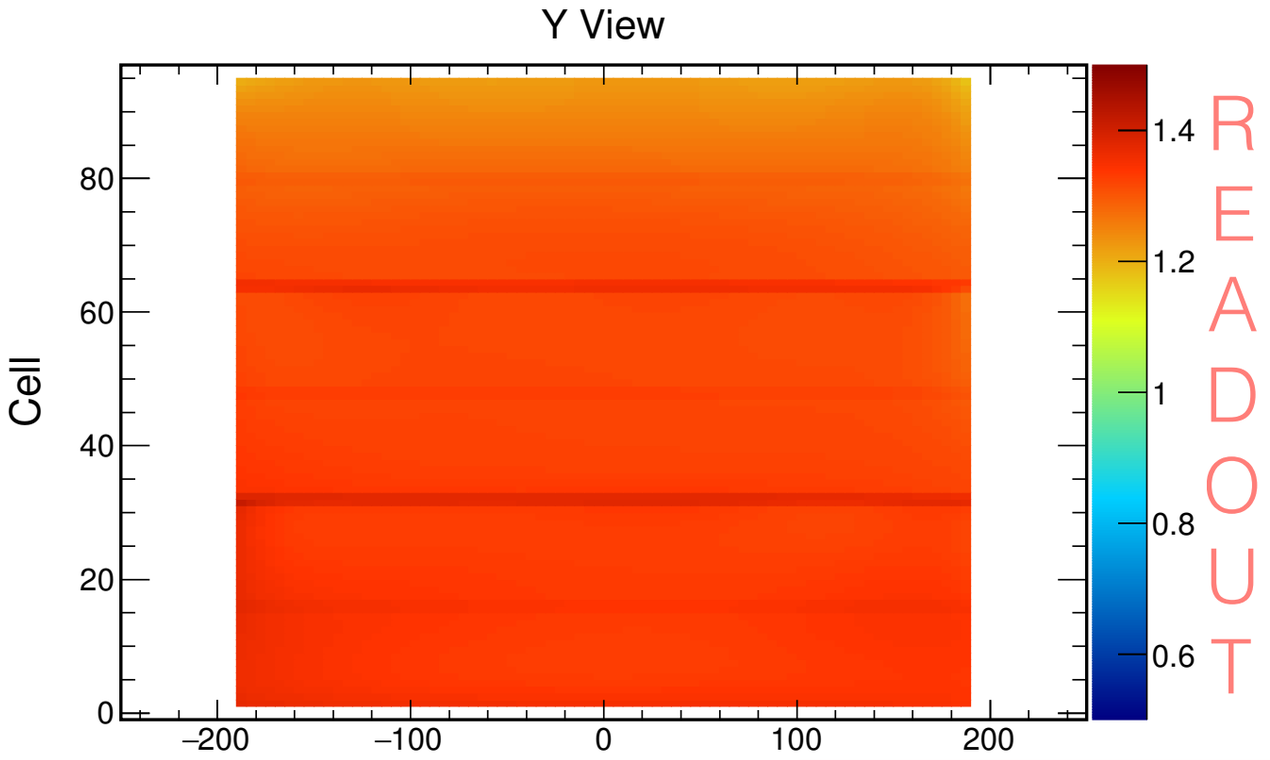
Energy Deposition is not uniform throughout the detector

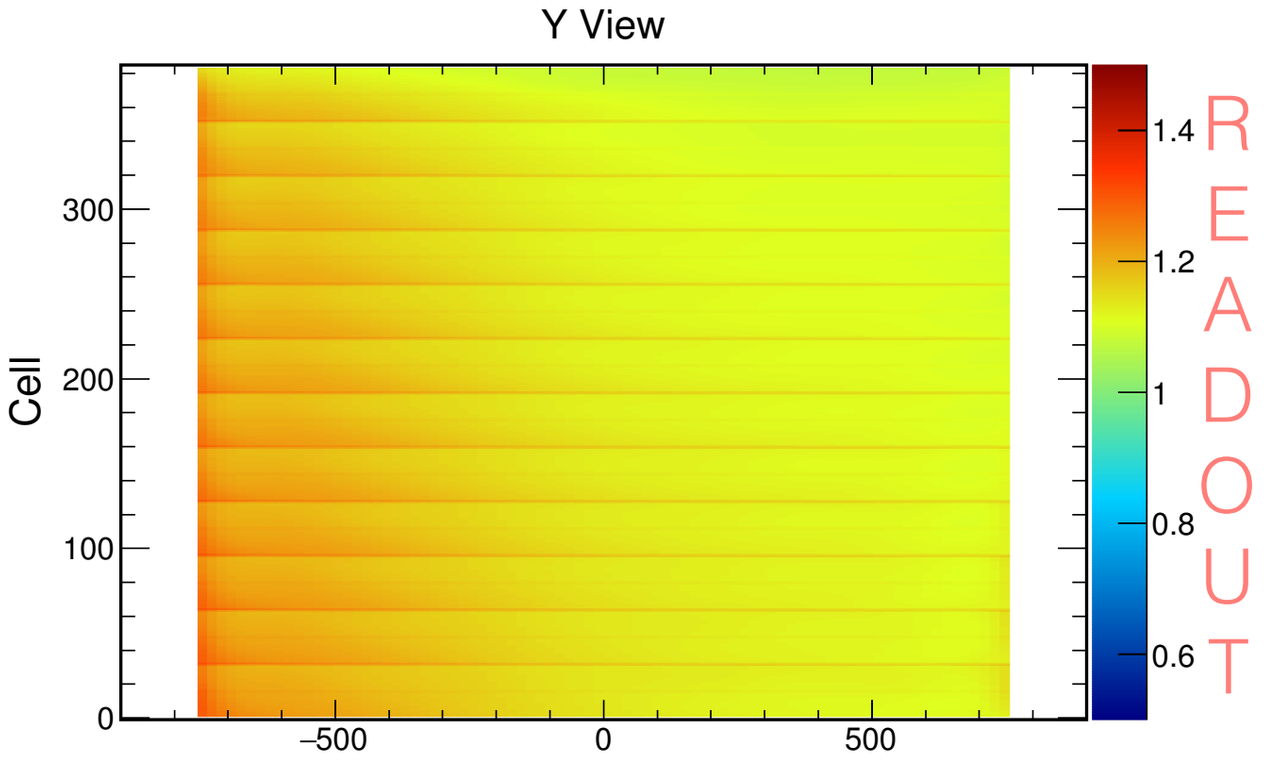




- Hits at the top of the detector tend to be further from track “end”
- The **true dE/dx is not uniform throughout the detector**
  - ✳ *lower parts of detector shielded by top*
- Folds into impact of threshold since lower-dE/dx areas tend closer to threshold (bottom horizontal cells)

Relative Correction Factors





W

Near Detector

Threshold & Shadowing Correction Factor

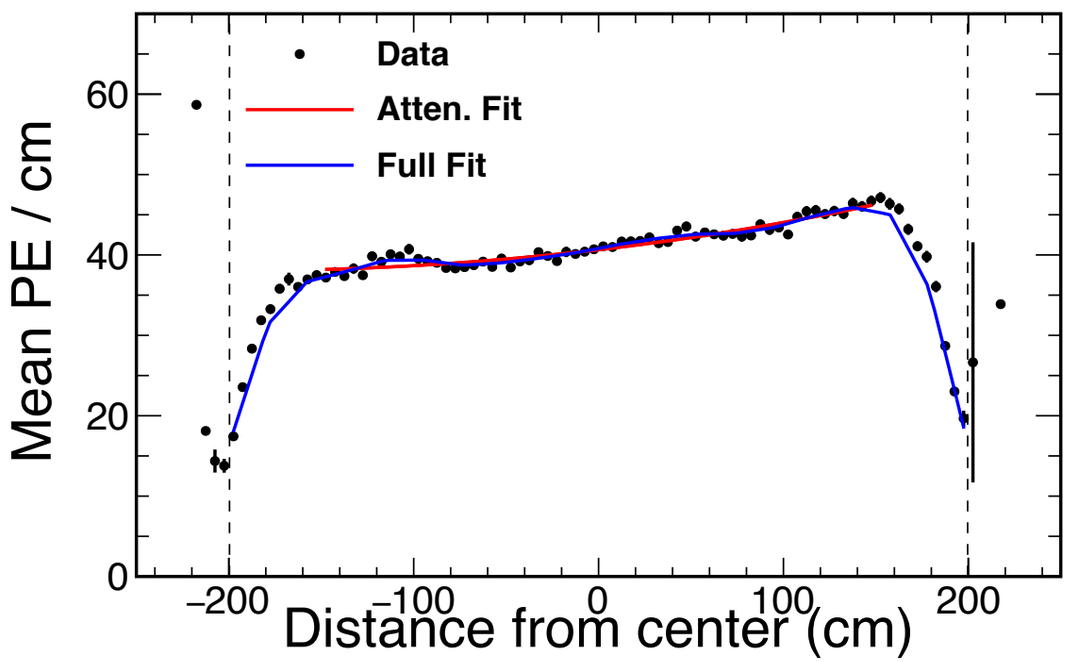
Attenuation Fit, each cell

W

Far Detector

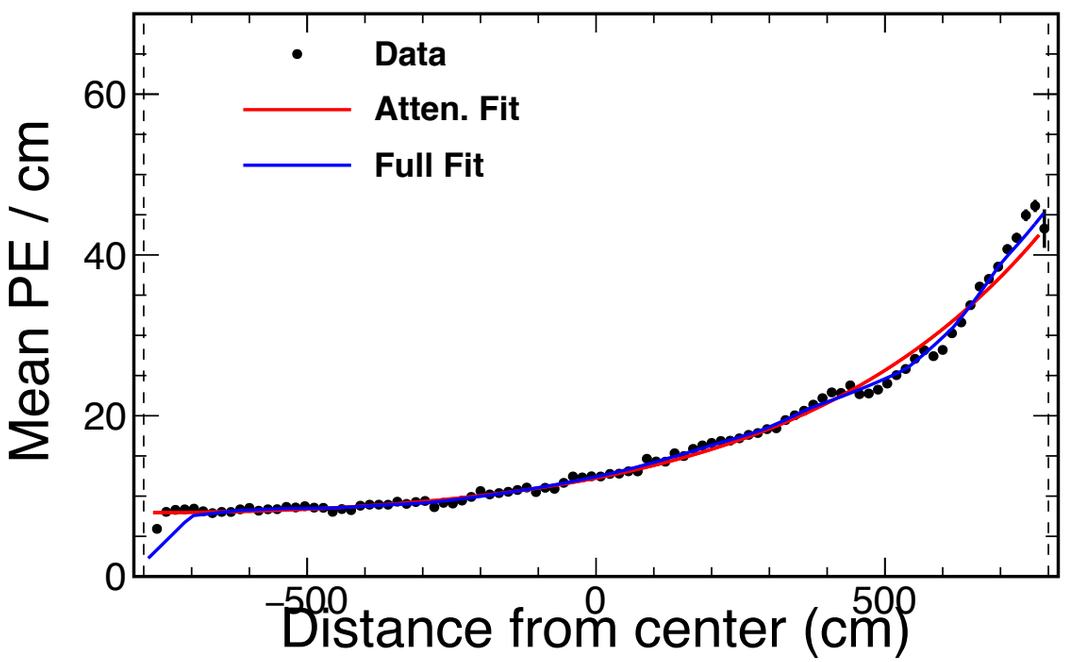
NOvA Preliminary

ND cosmic data - plane 48 (horizontal), cell 81



NOvA Preliminary

FD cosmic data - plane 2 (horizontal), cell 376

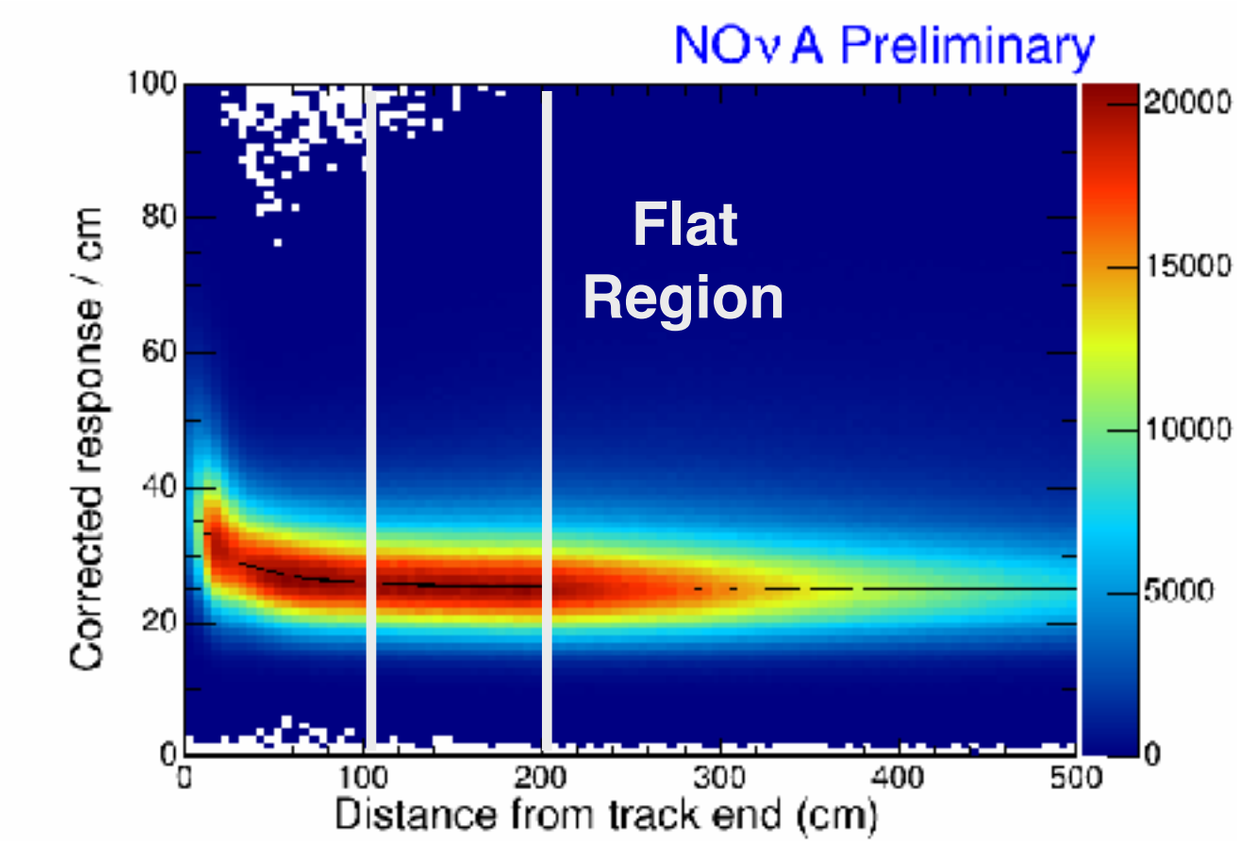


Absolute Calibration

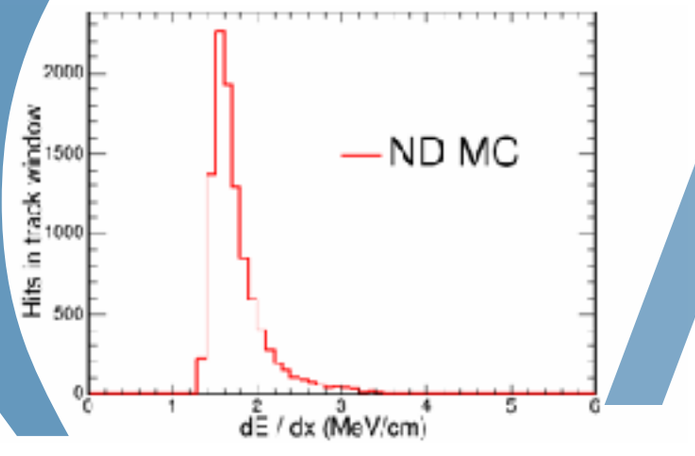
Energy Scale

$$PECorr_{\text{hit}} * \left(\frac{MeV/cm}{PECorr/cm} \right) = MeV_{\text{hit}}$$

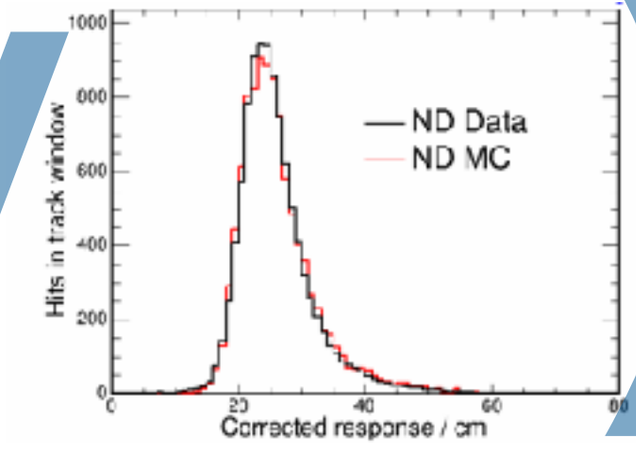
- Select **Stopping Muons**
- Tighten dE/dx peaks by selecting hits in the Bethe-Bloch flat region
- MC: True dE/dx and Response
- Data: Response (PECorr/cm)



MeV/cm

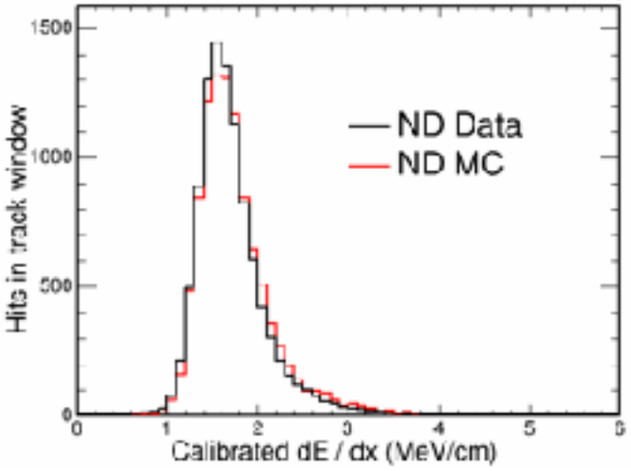


PECorr/cm

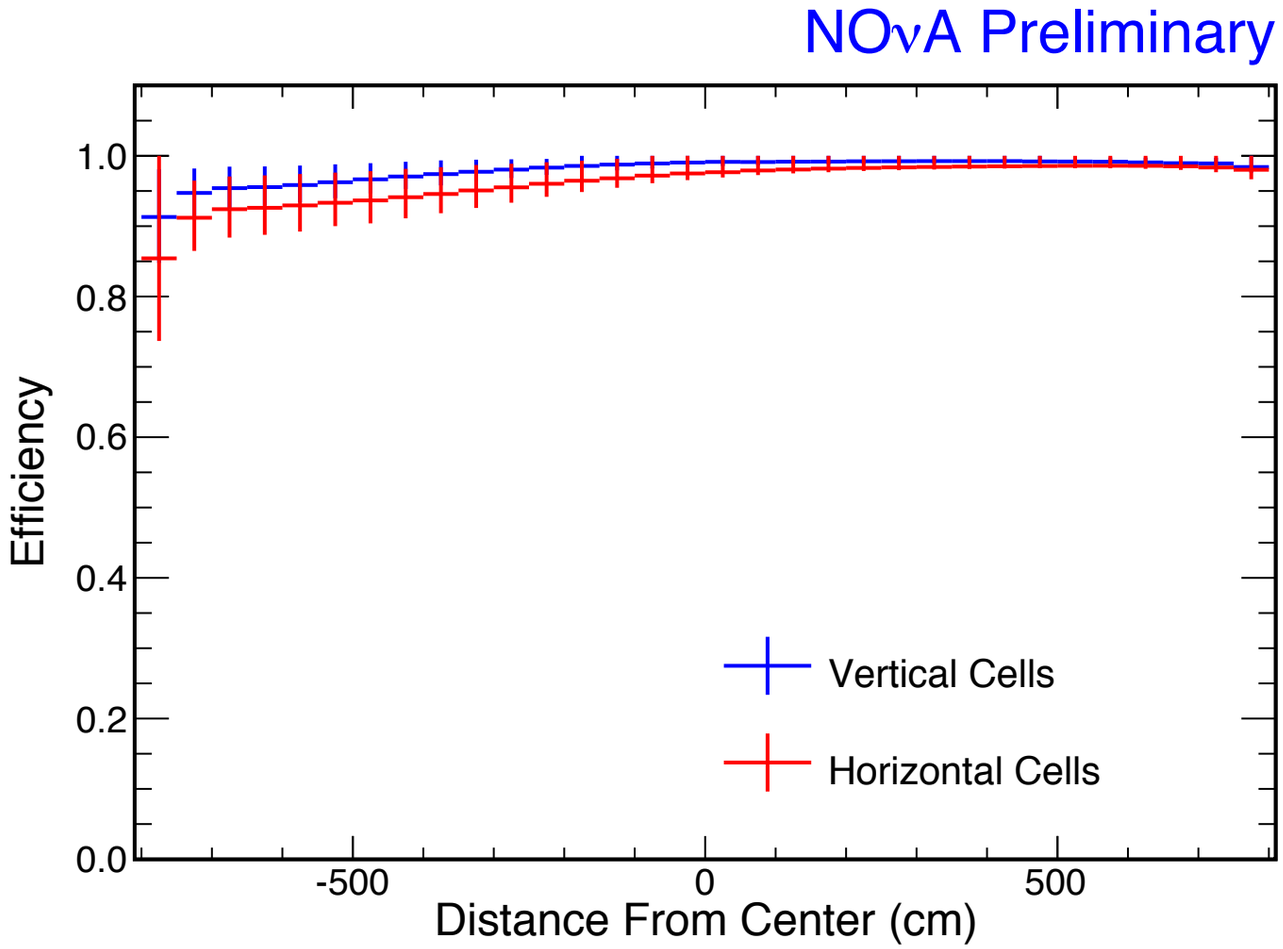


*** PECorr**

MeV/cm



Absolute Calibration

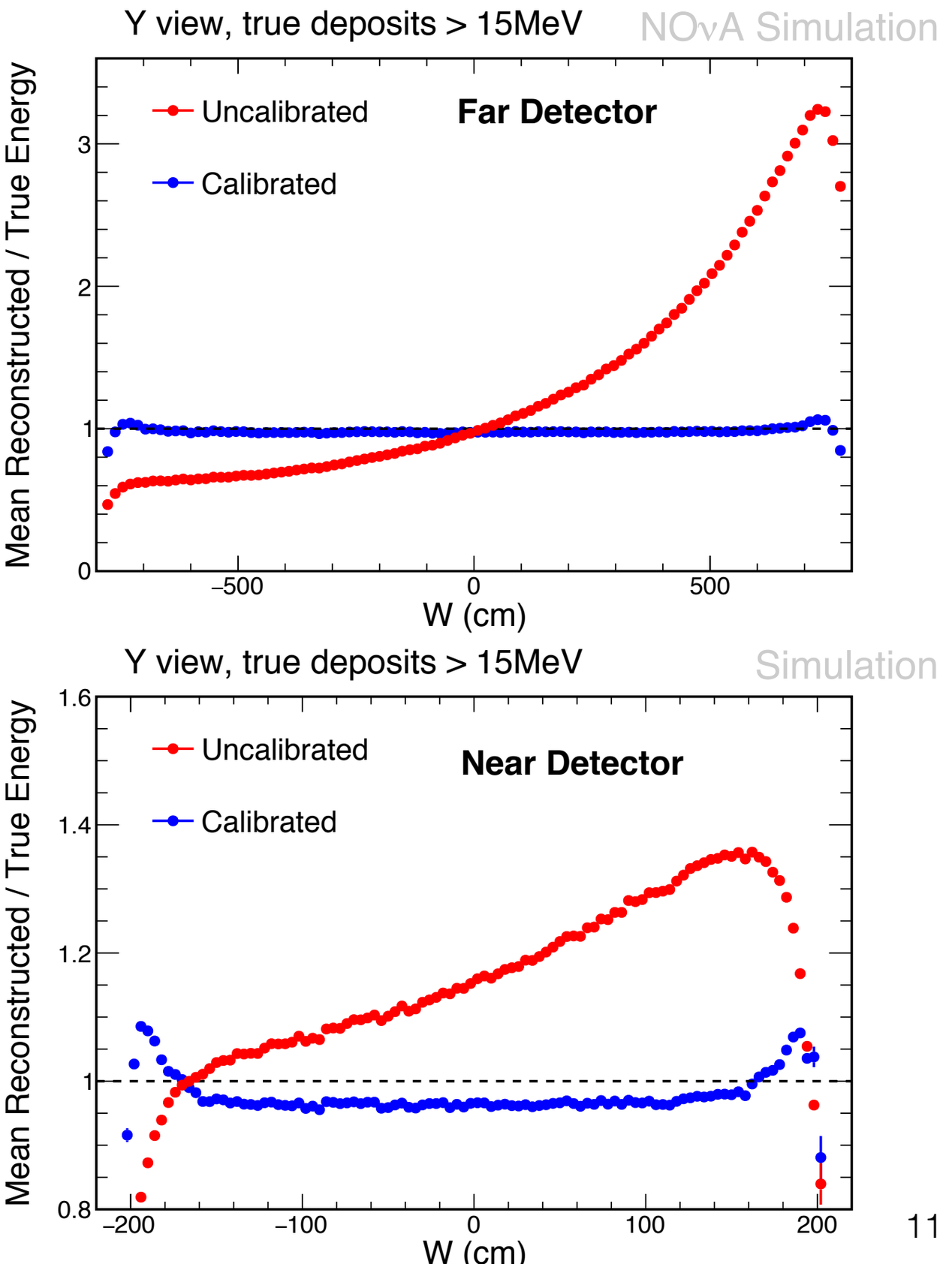


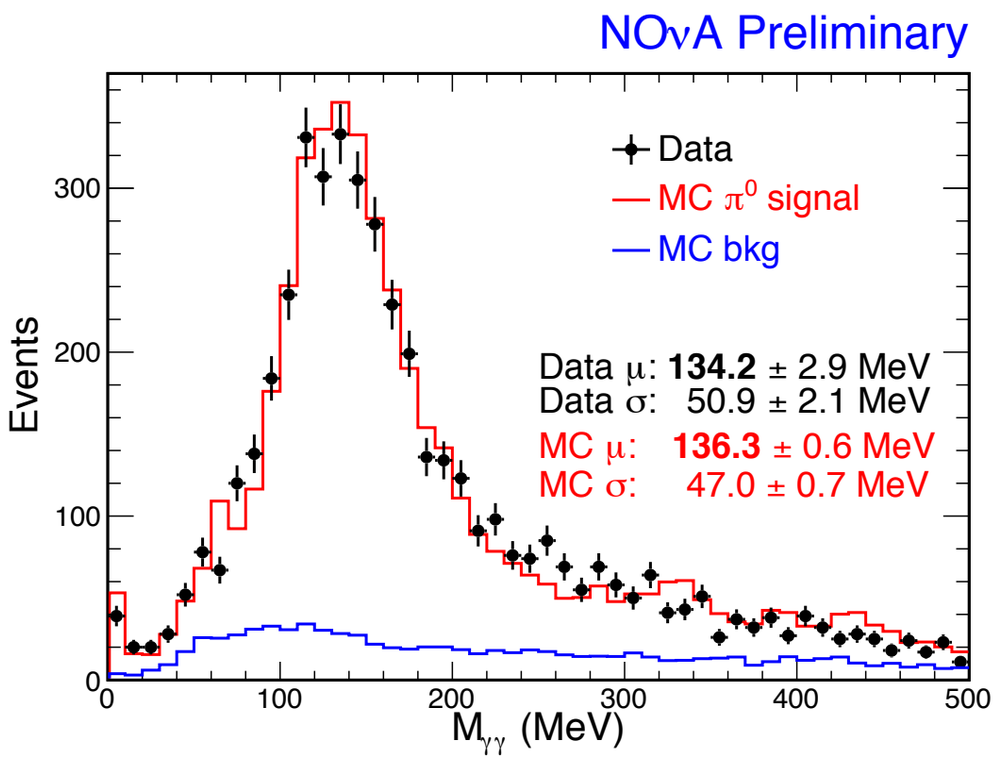
Far Detector Hit Efficiency

- Threshold means selected hits were more likely to be up-fluctuations in *true* energy deposition
  - Select only flat region of W so Energy scale is not biased
- Horizontal Y View has many more hits, calibrate separately and average

Verification with MC

- Profile Ratio of Reconstructed over True Energy
  - ✳ **Energy Scale**: average vertical deviation from 1
  - ✳ **Relative Calibration**: shape along W, cell, plane
- Pi-Zero Mass Peak
- Muon/Proton dE/dx
- Michel Electron Spectrum





Takeaway Points

- **Full chain of correction factors** to take measured PE to a best estimate of energy deposited, GeV

- **Scintillation Light attenuates** to different degrees in each cell
  - ✳ Fit a curve to PE/cm response for each cell: attenuation correction factor

- **Need to remove bias from the cosmic muon sample** before calibrating
  - ✳ Threshold and Shielding Effects

- Do not let **threshold effects bias the absolute energy scale**
  - ✳ <MeV / cm> / <PECorr / cm>

- Ongoing Work
  - ✳ Threshold & Correction Factor with data instead of MC
  - ✳ Rigorous understanding of systematic uncertainty

Backup

Combined Threshold & Shielding Correction

$$T = \frac{PE}{\lambda} * \frac{E_{\text{true}}}{E_{\text{MIP}}}$$

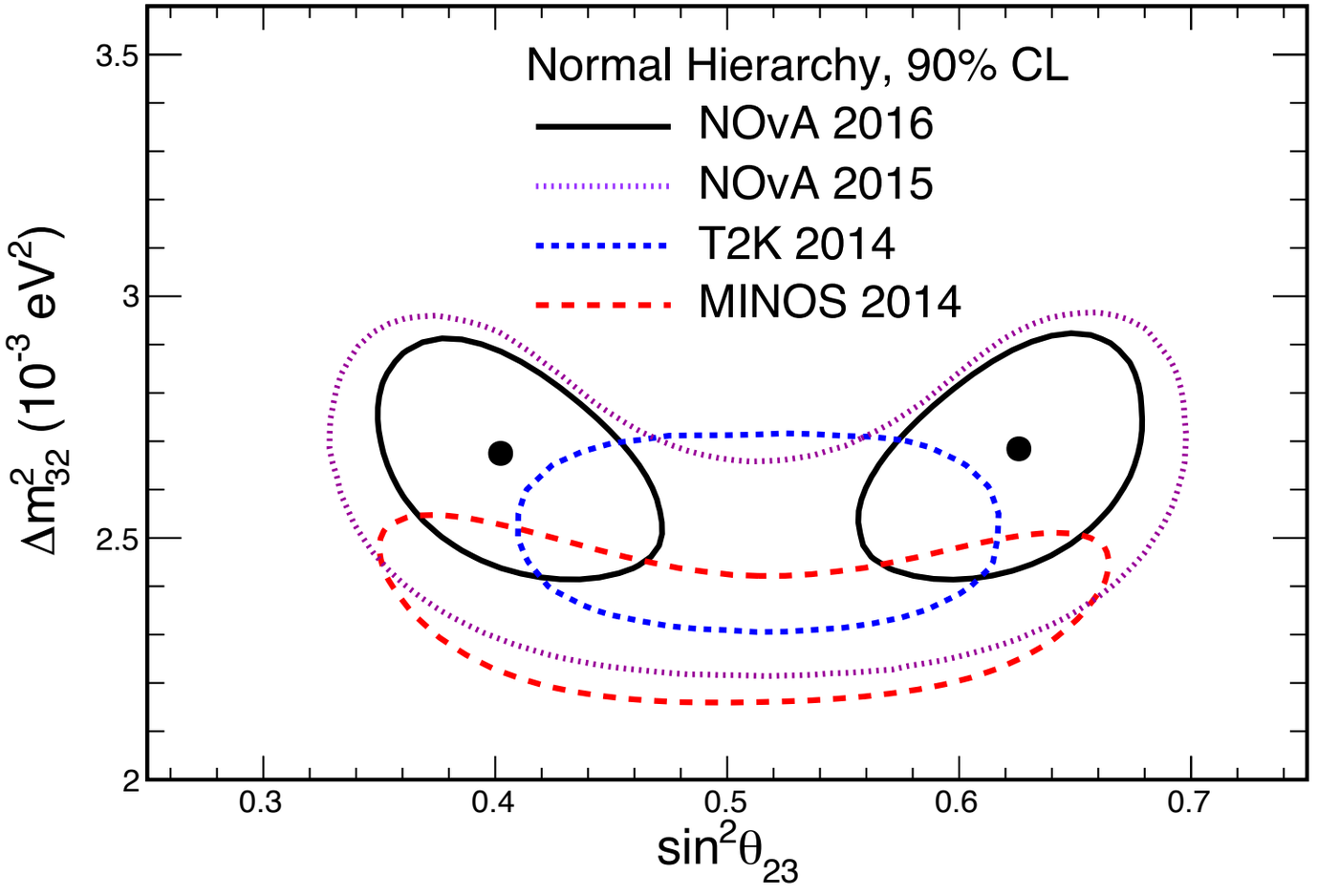
Threshold — — Shileding

- PE: Simulated photoelectrons at the readout
- **λ**: number of simulated photons expected at readout in the absence of fluctuations (PE is Poisson distributed)
- E_{true}: True energy deposited in cell
- E_{MIP}: Path length * dE/dx of minimum ionising particle

- Fill Cell x W plots with each MC Tricell hit from Cosmic Muons
- Empirical polynomial fit to resulting plot: Final Correction

NuMu-disappearance 1σ Uncertainty Table

Source of uncertainty	Uncertainty in $\sin^2\theta_{23}(\times 10^{-3})$	Uncertainty in Δm^2_{32} $(\times 10^{-6}$ eV$^2)$
Absolute muon energy scale [±2%]	+9 / -8	+3 / -10
Relative muon energy scale [±2%]	+9 / -9	+23 / -14
Absolute hadronic energy scale [±5%]	+5 / -5	+7 / -3
Relative hadronic energy scale [±5%]	+10 / -11	+29 / -19
Normalization [±5%]	+5 / -5	+4 / -8
Cross sections and final state interactions	+3 / -3	+12 / -15
Neutrino flux	+1 / -2	+4 / -7
Beam background normalization [±100%]	+3 / -6	+10 / -16
Scintillation model	+4 / -3	+2 / -5
δ_{CP} $[0 - 2\pi]$	+0.2 / -0.3	+10 / -9
Total systematic uncertainty	+17 / -19	+50 / -47
Statistical uncertainty	+21 / -23	+93 / -99



- NOvA 2015—>2016
  - Improvement mostly statistical

- **Impact of Calibration systematic uncertainty increasing with statistics**